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AN EMPIRICAL MODEL FOR NEAR MILLIMETER WAVE SNOW EXTINCTION AND BACKSCATTER (U)

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A snow extinction and backscatter model for near millimeter waves was developed to complete a set of natural atmosphere propagation models for inclusion in the Electro-Optics System Effects Library (EOSAEL) (1). This model is compact, simple, fast, and uses commonly available meteorological data as inputs. The accuracy is commensurate with the accuracy of those input parameters; where the input parameters do not properly characterize the environment, further input specification is available. For snow, the rain equivalent accumulation rate is the fundamental input, with air temperature providing the distinction between dry and wet snowtypes. For millimeter wave (MMW), the classification of the snowflake by its ice-to-liquid-water ratio is necessary, due to the large differences in the complex indices of refraction of ice and water (2).

The snow extinction model is presented first, including a review of the data used to generate it. The backscatter model is then discussed, followed by a comparison between the model and measurements made at the Cold Regions Research and Engineering Laboratory (CRREL) SNOW-ONE test in January-February 1982 (3).

1. SNOW EXTINCTION

While the literature on the interaction of MMW with snow is limited, the complete literature will not be reviewed here; a general review has been carried out by Kobayashi (4). Only those results used in the model will be discussed.

The general classification of snowtypes is discussed in detail by Nishitsuji (5). Four types are described: dry, moist, wet, and watery, distinguished by the density of the snowflake. Because no other determination of snowflake density was reported in the literature, it is difficult to follow this classification procedure; in practice, snowtypes were

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inferred by comparison with the Nishitsuji extinction results where possible. Data for extinction by wet snow at 15 GHz, moist snow at 35 GHz, and watery snow at 50 GHz are presented. A Mie scattering type model was developed by Nishitsuji, but is cumbersome, and only his experimental results were employed.

Data at 11, 15, 24, and 48 GHz are presented by Oomori and Aoyagi (6), although no indication of the snowtypes is given. A unique confocal resonator was used to measure snow attenuations. Comparison with other data seems to indicate that moist snow propagation was measured. The data are modeled with an aR^b relation, which is derived using a theory of snowfall statistics and in which R is rain equivalent snowrate and a and b are parameters. The a parameter data agrees well with other data, but at 24 and 48 GHz there is poor agreement for the b parameter.

Moist snow data is provided at 35 GHz by Robinson (7). The data set is of limited extent, having only seven useable values. Malinkin et al (8) measured dry snow at 35 GHz, with but a slight improvement: eight points.

Only two data points exist in the literature for frequencies above 50 GHz: one at 140 GHz for wet snow by Richard, Kammerer, and Reitz (9), and one at 312.5 GHz for dry snow by Babkin et al (10). The Richard paper also reports visual range for the same snow data. Readers should note the error in reference (9), figure 25, where the a parameter is written as 1.37 but clearly should be 3.7 instead.

Analysis of the data shows that an aR^b relation for snow is the simplest form for a snow model, but does such a model have theoretical foundations? A review of aR^b models for rain extinction provides the guidelines.

Relations of the form aR^b can be derived for rain in the Rayleigh and optical limits. This result relies on the use of negative exponential or modified gamma dropsize distribution and a power series representation for the particle forward scattering amplitude. Where such power series representations cannot be found, direct fits to Mie scattering calculations are used. Such models provide highly accurate results for only a limited range of rainrates, but application over wider ranges is useful because of the general dominance of errors introduced from the beginning by the arbitrary raindrop size distribution. Errors can be significant, but may be minimized by the judicious selection of raindrop distribution (11).

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Errors in the snow model can be expected to be even larger. Errors of drop or snowflake distribution are compounded by the snowflake orientation dependence of the forward scattering amplitude, which now is due to a highly asymmetric flake or aggregate. Some of this asymmetry will be reduced by volume averaging over the falling snowflake orientations, but large variations due to snowflake type must be anticipated. The similiarity or lack thereof between the a and b parameter frequency and particle size dependencies will indicate how complete this averaging process is. For snowflakes that are truly amorphous, with no orientation forces in free fall, this technique should provide a reasonable model. This cannot be expected to be true for all snowtypes. If flake orientations are not random, then significant fluctuations in extinction and backscatter from the model will occur. Because this model neglects polarization, it must also be used cautiously, since polarization effects can be expected to be large for snow. The treatment of polarization and snowflake orientation are beyond the scope of a model of this type. There are probably few, if any, models that can even attempt to treat these effects in a general manner for snow.

The a parameters taken or derived from the literature are shown in figure 1 along with the various distribution parameters used in a corresponding rain model. The scarcity of snow data is evident, but the data are consistent with expectation. Dry snow, representing pure ice crystals and air, has small MMW refractive indices relative to liquid water, and correspondingly low extinction. As snow becomes wetter, its scattering cross section increases dramatically—an effect seen as the radar "bright band." At higher frequencies, as scattering approaches the optical limit, the cross section evidences a $^1/R$ dependence. Dry snow, with its predominance of small flakes, has less extinction at low frequencies, but as the optical limit is approached the relationship of dry and wet snow extinction will reverse, giving dry snow greater attenuation than wet snow. Where this crossover point occurs is not indicated in this data set. All the curves pass through the 312 GHz point for lack of data at these high frequencies.

The use of an aR^b relation for snow is supported by this data, which does not display large unexpected variations from the rain cases. Note that at low frequencies, below 35 GHz where the Rayleigh approximation applies, the curves for wet snow and rain do not converge, due to refractive index differences and to the fact that the extinction is expressed as a function of accumulation rates, not mass density.

The b parameter, which determines the dependence of extinction on accumulation rate, is shown in figure 2, again with rain values and the inferred frequency and snowflake behavior.

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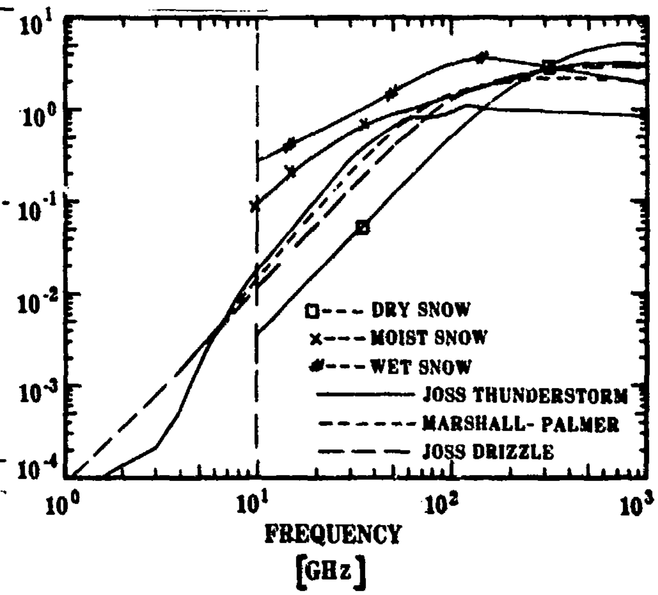

Figure 1. Snow parameter a with rain comparison.

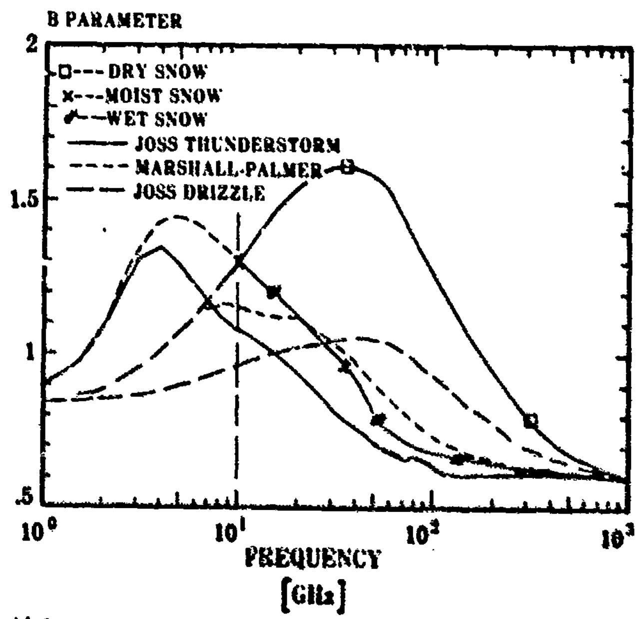

Figure 2. Snow parameter b with rain comparison. Data extrapolated below 10 GHz

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The wet and moist snow data are similar to the Joss thunderstorm and Marshall-Palmer behavior; these curves have been roughly followed in defining the wet and moist snow b parameter curves. Dry snow behavior is expected to follow the Joss drizzle distribution due to the predominance of small particles in both cases. However, two points provide only the crudest indication of the dry snow behavior. The large peak value of the dry snow b parameter should not cause alarm, because dry snowrates are generally quite low, there being little or no data for rates above 2 mm/h in the literature.

Air temperature at the ground is used to determine the snowtype for an extinction calculation. Dry snow is used at or below freezing, moist snow paremeters are used from 0°C to 2°C, and wet snow is employed above 2°C. These temperatures are rough estimates, based upon the assumption that temperature lapse rates are negative and are subject to adjustment depending on the specific storm characteristics.

The frequency range covered by this model is not well defined. With eight data points defining three curves and with only two measurements above 50 GHz, the high frequency behavior of the model is obviously subject to error. For this reason, use of the model above 100 GHz should be accompanied with caution.

2. SNOW BACKSCATTER

MMW snow backscatter data is severly limited by the use of inferred reflectivity factors derived from measured snowflake size distributions. Such results are valid only in the Rayleigh regime below 35 GHz. Initially, a Rayleigh model was employed with restricted frequency coverage. With the publication of a datum at 95 GHz resulting from the SNOW-ONE measurements, it was decided, due to the inadequacy of the existing model, to develop a new model using all the available data. No validation of this model is possible because all the data were incorporated in it.

The similar behavior of the rain and snow a and b parameters led to the use of the rain backscatter model to provide the shape of the snow backscatter curves. This procedure can be dangerous, but theory and experiment are not yet able to provide sufficient knowledge to define an independent model. At long wavelengths, the reflectivity factors of Imai et al (12) are used along with the Rayleigh relation to compute backscatter cross section, η,

$$\eta = \frac{\pi |k|^2}{\lambda^4} Z$$

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where $k = (m^2 - 1)/(m^2 + 2)$, m is the complex index of refraction, λ the waveleugth, and $Z = \int N(D)D^6\, dD$ where N(D) is the snowflake size distribution function. In practice, reflectivity is related to rain equivalent snowrate as

$$Z = aR^b .$$

Table 1 lists the values of the a and b parameters from Imai et al, where their classification is assumed to correspond with our dry, moist, and wet classes.

TABLE 1. RAYLEIGH BACKSCATTER PARAMETERS

Snowtype	a	b
dry	600	1.8
moist	1800	1.8
wet	2400	1.8

At shorter wavelengths, the rain backscatter curve was forced to go through the datum from Nemarich et al (13) at 95 GHz. Their nine data points were abstracted into a single upper bound value. This was necessary because their data did not correlate well with the snow accumulation data, an apparent example of snowflake resonant scattering variations. The value used was $6.6 \times 10^{-5}\ m^2/m^3$ for a dry snowrate of 1 mm/h. Examples of the computed snow backscatter cross sections for the three snowtypes and a snowrate of 5 mm/h are shown in figure 3. Comparison with rain backscatter indicates that for dry snow the cross section is much less for snow; for moist snow, rain and snow are comparable; and for wet snow, snow backscatter is much larger than rain.

In scaling the snowtype results, it was assumed that the Imai et al results would hold at all frequencies, thus giving moist snow three times and wet snow four times the dry snow cross section. This may not be correct, but no data are available yet to improve the assumption.

3. MODEL EVALUATION

The SNOW-ONE test (3) of January and February 1981 provided the first opportunity to evaluate the snow extinction model using a totally independent data set.

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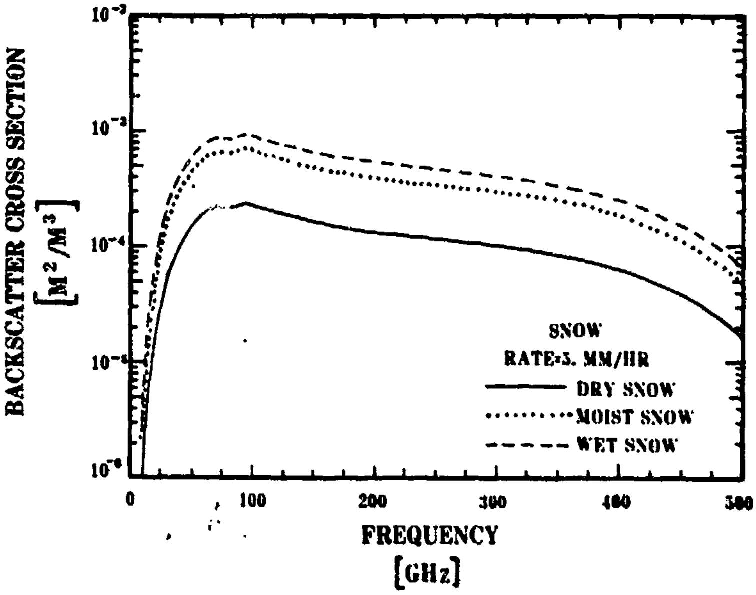

Figure 3. Snow backscatter cross section.

Both Harry Diamond Laboratories (HDL) and the US Army Ballistics Research Laboratory (BRL) carried out MMW propagation experiments at SNOW-ONE. The HDL Mobile Measurement Facility, operating at 95, 140, and 225 GHz, measured extinction and backscatter, reported by Nemarich et al (13). The BRL experiment measured extinction at 35, 95, 140, and 217 GHz, reported by Bauerle and Knox (14). Due to the small data sample at 35 GHz, this frequency is not included in the evaluation.

Supporting meteorological and snow characterization data have been provided by CRREL (3) and the US Army Atmospheric Sciences Laboratory (15).

The most significant storm of the test, beginning at 0400 on 8 February and finishing at 0500 on 9 February, was selected for analysis. Snow accumulation data was available from 1700 on the 8th to 0400 on the 9th. At 2200 on the 8th windspeeds increased, producing significant amounts of blowing snow and ending the capability of the snow accumulation gauges to indicate the amount of airborne snow. Therefore, only the data from 1700 to 2200 on 8 February are suitable for comparison with the model predictions. To provide a sense of the variations in extinction, the data for the period from 1700 on the 8th to 0400 on the 9th will be presented.

The millimeter transmission data was reported relative to the clear path transmission determined either before or after the storm. The measurements do not correct for temperature and relative humidity variations during the storm, but the relative humidity remained above 95 percent during this period, and temperature variations are estimated to introduce at most errors of ±0.06 dB/km at 95 GHz, ±0.15 dB/km at 140 GHz, and ±0.4 dB/km at 220 GHz. These are small enough to be neglected.

The presence or absence of fog during the storm can influence millimeter extinction. Light scattering instruments were used to measure aerosol size distributions, but their results are not easy to interpret. At the succeeding SNOW-ONE-A test held in Dec 81 and Jan 82, a background aerosol was measured at all times, presumably due to the wood stoves used to heat many houses in the region. At SNOW-ONE this background aerosol was not anticipated and therefore not measured. It is not possible to separate unequivocally the fog or smoke aerosol contribution to the aerosol distributions measured at SNOW-ONE. During the period from 1700 to 2200, equating all the measured aerosol with fog provides only a maximum of 0.035 gm/m^3 of fog liquid water, and generally much less. This corresponds to a maximum of 0.17 dB/km at 95 GHz, 0.24 dB/km at 140 GHz, and 0.29 dB/km at 220 GHz, all less than 10 percent of the extinctions measured during that time. Apparent fog densities did increase dramatically after 2200, but this was certainly due to the blowing snow.

Rather than compute the extinction from the measured snowrate, the measured snow extinction was used in an inverse calculation to predict the snow accumulation rate. This was done to provide the most concise temporal presentation of the three frequency results. Figures 4 and 5 show the "inverse" model predictions compared to the measured snowrate for the BRL and HDL data, respectively. Conversion from moist to dry snow at 1850, following the temperature decrease, has been made. For the period from 1700 to 2200 the agreement is quite good for an empirical model with such a limited data base. The peak at 217 GHz in the BRL data at 2100 is not repeated in the HDL data and cannot at this time be explained. The consistency of the model is very good, and it is tempting to conclude that the snow accumulation measuring equipment slightly undersamples. Such a conclusion is unwarranted, but does indicate that traditional snowrate measurements are really not adequate for the detailed characterization required by this data.

The large excursions after 2200 are due to the blowing snow, but the disagreement between the HDL and BRL results at 225 and 217 GHz may be due in part to improper calibration of the HDL 225 GHz data because the correct calibration was not yet available. Since this snow model cannot address the conditions after 2200, discussion is academic at this time.

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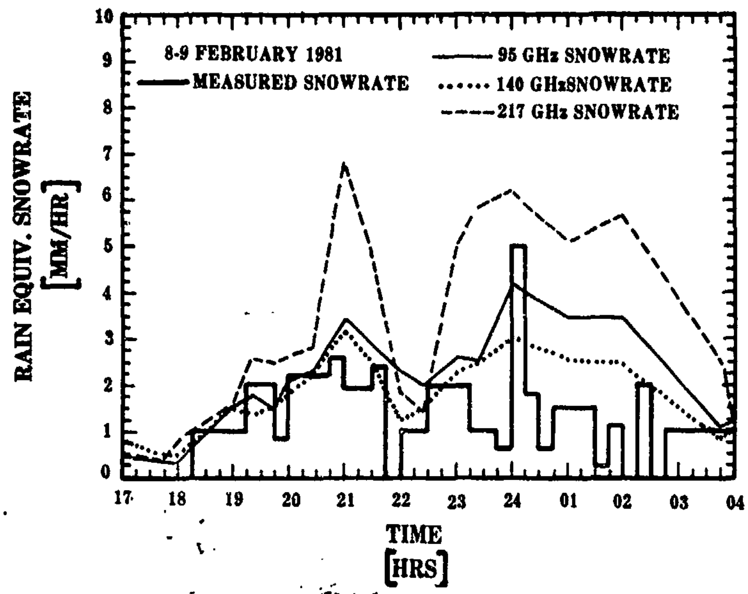

Figure 4. Snowrate computed from BRL data compared to measured snow-rate.

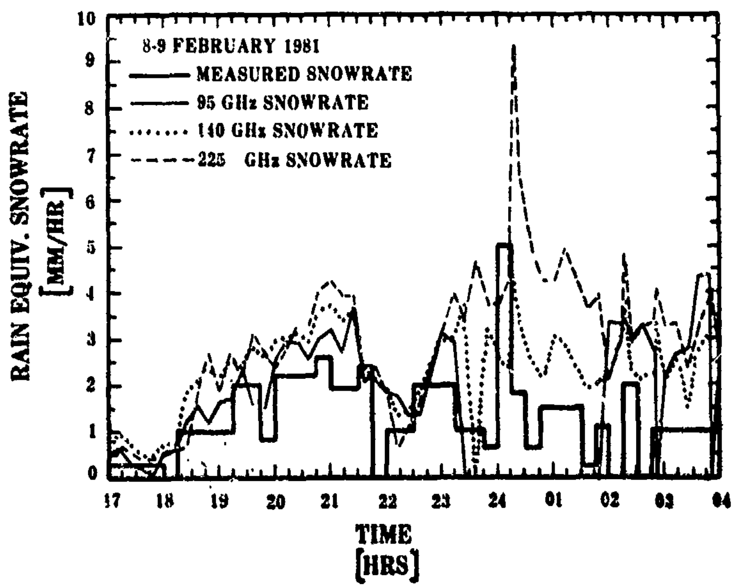

Figure 5. Snow rate computed from HDL data compared to measured snow-rate.

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These results give added confidence to the use of the model at frequencies up to 225 GHz, at least for dry snow. Wet and moist snow accuracy must still be determined at these high frequencies. Given existing field test programs, it is unlikely that measurements above 225 GHz will be available, so that extension of the model with confidence above this frequency may not be possible.

4. CONCLUSION

A new MMW snow model has been presented, based upon the use of an aR^b relation. The data used in its development were briefly reviewed, and the similarity of the snow and rain models was shown. The extinction model was compared with independent data from two separate facilities and demonstrated remarkably good agreement. The backscatter model could not be evaluated because no independent data exist.

The development of this model has clarified three data deficiencies: lack of snow backscatter data from all types of snow, lack of polarized propagation data at all frequencies, and lack of unpolarized data at frequencies above 100 GHz. Efforts to provide for the inadequacies of the data base continue, but snow data is difficult to obtain, and further development of the model will be slow.

A particular problem is that a large data base is necessary at each frequency to define the a and b parameters, due to the use of snowrate as the fundamental quantity. This also limits the model to near calm conditions, since there is no way to estimate the effects of blowing snow. A more sophisticated model using airborne snow density or the snowflake size distribution function itself could be developed, but the data set would be even smaller than that employed here. Since these data are not part of the standard meteorological data base, it would be most difficult to apply such models over various geographic and diverse climatological areas. For these reasons, this empirical MMW snow extinction and backscatter model is offered as a solution to the predictive problem of the effects of snow on MMW propagation.

5. REFERENCES

1. Duncan, Louis D., EOSAEL 80, Volume 1, Technical Documentation, ASL-TR-0072, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico, 1981.

2. Ray, P. S., "Broadband Complex Refractive Indices of Ice and Water," Applied Optics, 11:1836-1844, 1972.

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Author Affiliation City, State

First line

3. Redfield, R. K., ed., SNOW-ONE Preliminary Data Report, Internal Report #715, US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1981.

4. Kobayashi, Herbert K., Effect of Hail, Snow, and Melting Hydrometeors on Millimeter Radio Waves, ASL-TR-0092, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico, 1981.

5. Nishitsuji, A., "Method of Calculation of Radio-Wave Attenuation in Snowfall," Elect and Comm in Japan, 54-B:34, 1971.

6. Oomori, T., and S. Aoyagi, "A Presumptive Formula for Snowfall Attenuation of Radio Waves," Elect and Comm in Japan, 54-B:74, 1971.

7. Robinson, N. P., "Measurements of the Effect of Rain, Snow, and Fogs on 8.6 mm Radar Echoes," Proceedings IEEE, 203-B:209, 1955.

8. Mahlinkin, V. G., et al, "Attenuation of Signal at the Wavelength $\lambda = 8.6$ mm in Hydrometeors," Rad Eng and Elect Physics, 21:1, 1976.

9. Richard, W. W., J. E. Kammerer, and R. G. Reitz, "140-GHz Attenuation and Optical Visibility Measurements of Fog, Rain, and Snow," Memorandum Report ARBRL-MR-2800, US Army Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, 1977.

10. Babkin, Yu. S., et al, "Attenuation of Radiation at a Wavelength of 0.96 mm in Snow," Radio Eng and Elect Physics, 15:2171, 1970.

11. Keizer, W., J. Snieder, and C. de Haan, "Rain Attenuation Measurements at 94 GHz: Comparison of Theory and Experiment," DPP Symposium, Neubiberg bei Munchen, Germany, 1978.

12. Imai, I., M. Fujiwara, I. Ichimura, and Y. Toyama, "Radar Reflectivity of Falling Snow," Meteorology and Geophysics (Japan), 6:130, 1955.

13. Nemarich, J., R. J. Wellman, D. Rocha, and G. B. Wetzel, "Characteristics of Near-Millimeter Wave Propagation in Snow," SPIE, Vol 305, in press.

14. Bauerle, D., and J. E. Knox, "Millimetre Wavelength Radar Propagation and Backscatter Measurements at SNOW-ONE," Snow Symposium I, in press.

15. Olsen, R. O., D. R. Brown, J. E. Butterfield, and R. Orkasiuski, "SNOW-ONE Atmospheric and Transmission Measurements," Snow Symposium I, in press.

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